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Assessing the role of steam power in the first industrial revolution: The early work of Nick von Tunzelmann

Kristine Bruland[a], Keith Smith[b,*]

[a] IAKH, University of Oslo, Norway
[b] Centre for Innovation and Entrepreneurship, Imperial College, London, United Kingdom

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ABSTRACT

This article considers the historiographical and theoretical significance of Nicholas von Tunzelmann's first book, *Steam Power and British Industrialization to 1860*. Von Tunzelmann assessed the quantitative impact of the Watt steam engine and its pirate copies on the British economy using the social savings method pioneered by R.W. Fogel, showing that the impact was smaller and later than many historians had supposed. These results are of more than quantitative significance because they call into question a dominant line in the history of industrialization that focuses on the steam engine as a key determinant of the dynamics of industrial growth in Britain from the late eighteenth century. This article discusses the origin of this line in the work of Arnold Toynbee and outlines its long-term influence on economic history, including contemporary debates on the question of why Europe outpaced China and India from the seventeenth century. These issues are important also for innovation studies, which often describes the relation between innovation and growth in terms of such 'critical technologies' as steam power; these accounts are subject to the same weaknesses as technicist histories of industrialization. Von Tunzelmann's early work is therefore of continuing theoretical and empirical significance as we seek an adequate theory of the links between innovation and growth.

1. Introduction

There are many reasons to honour Nick von Tunzelmann, but one of them is the path-breaking character of his early work. This paper discusses some of the conceptual and historiographical implications of his first major book, *Steam Power and British Industrialization to 1860*, published in 1978. Our view at the time was that his work contributed not only to the history of steam power directly, but was also fundamentally important for understanding the nature of the first industrial revolution and the character of long-term economic dynamics more generally (Bruland and Smith, 1981). Here we reconsider the book thirty years on, drawing on our previous assessment and looking at what has happened since.

2. The issues: steam power and the dynamics of growth

The specific issue raised by von Tunzelmann's work is the quantitative impact of steam power on British national income, from the early industrialization of the late 18th century to the consolidated industrial economy of 1860. But it raises a much wider question to do with how radical innovations relate to economic change. The importance of *Steam Power and British Industrialization to 1860* is that in investigating the relations between the diffusion of James Watt's engine and the growth of the British economy as a whole, as well the specific effects on some related sectors, it provides "the first detailed critique of the 'energy crisis' interpretation that is implicit or explicit in many of the best-known histories of the industrial Revolution" (von Tunzelmann, 1978, p. 8). But this exploration leads on to major issues about the causal links between innovation, industrialization and growth.

Researchers in innovation studies and innovation economics tend to be familiar with the alleged roles of steam power, mechanized textile technologies and other radical innovations via theories of growth based on long waves of techno-economic development. This line of thinking was initiated by Kondratiev, elaborated by Schumpeter, and formalized most recently by Chris Freeman, Francisco Louça and Carlotta Perez (Freeman and Louça, 2002; Perez, 2002). These authors write the history of large-scale economic change around "critical technologies" that have large-scale generic effects, creating "techno-economic paradigms" that initiate and focus patterns of investment, chains of innovation and financial commitments. The breakdown of the paradigm is argued to be linked to financial crisis, and so this literature relates structural crises in capitalism to the trajectories of radical technologies. A related influential literature is the growth theory based on "General

* Corresponding author at: Innovation and Entrepreneurship Group, Imperial College Business School, London SW7 2AZ, United Kingdom. Tel.: +44 7500 393 816.
E-mail address: keith.smith@imperial.ac.uk (K. Smith).

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Purpose Technologies" (GPTs) (beginning with Helpmann, 1998). Within the GPT literature, the approach sees the technology as the primary determinant of change, but tends to take a more cautious view on timing, recognizing that the critical technologies may take a long time to develop (see for example the major attempt to build a growth theory on GPTs in Lipsey et al., 2005). The detailed history of steam power is important in these theories because the validity of the theories is closely dependent on whether or not the critical technologies do in fact have the impacts that are claimed for them, and dependent on whether the technologies play the causal role in growth and change that is assigned to them. Within the wave tradition, authors usually see steam as an emblematic device of the industrial era and the first Kondratiev wave, unleashing both structural change and an investment cycle. Some authors in essence accept the wave approach but add to it by seeking an explanation of how the relevant critical technologies emerged, with state sponsorship being a favoured factor (for example, Moe, 2007).

It should be noted that the critical technology approaches to growth were not original to Schumpeter, and arguably the GPT approaches are not particularly new either. Rather, steam power and its allegedly revolutionary growth and transformation effects have been central to economic histories of the industrial revolution for a long time, in a tradition that derives from the writings of Arnold Toynbee in the late nineteenth century. In this tradition, steam power was, in T.S. Ashton's formulation, "the pivot on which industry swung into the modern age" (Ashton, 1968, p. 19). Toynbee had a powerful influence on the economic history of industrialization. So von Tunzelmann's work is relevant not only to the modern innovation-based growth theory that succeeded his work, but to long term themes in British economic history that preceded it. However the economic history of industrialization has continued to develop, and indeed has extended into major debates on the evolution of the global economy that offer new perspectives on innovation and growth.

The remainder of this paper is in three parts. In the first we outline the particular way in which steam power was integrated into early histories of industrialization by Toynbee, and how it became central to the historiography of the "Industrial Revolution". In the second part we overview von Tunzelmann's work on steam power, and discuss its implications not only for measuring but also for conceptualizing industrialization. Finally, we discuss economic history since *Steam Power and British Industrialization*. Steam and coal remain central in some recent works of global economic history – especially the works of Kenneth Pomeranz and Robert C. Allen – that seek to explain why Britain and then the rest of Europe industrialized while India and China lagged. The global changes initiated by industrialization are now an area of considerable debate among historians (see O'Brien, 2010 for a comprehensive discussion), and so von Tunzelmann's work resonates outwards into large-scale contemporary issues and debates.

3. Conceptual origins of the "industrial revolution"

The term "industrial revolution", around which historical discourses on late eighteenth- and early nineteenth century Britain tend to be constituted, is a familiar one. It has provided the basic object of investigation, and the general context of specific arenas of research, for a large historiographical enterprise from which an important element is missing, namely an exploration of the theoretical background of the term "industrial revolution" itself. Too often, the term is treated as though its content is transparently plain. But the category does have, of course, a theoretical history of its own, and its mode of constitution has had significant effects, the most important of which has been to establish what might be called a "critical technology bias" at the core of British economic history. This bias consists in according analytical pride of place in economic history to the innovation of disruptive products and processes, and their impacts on output and fixed capital investment, in a small group of leading sectors. The wider multi-sectoral spread of innovation, and the less tangible organizational and structural changes of the period, are subordinated to technological change in the critical sectors, or sometimes even seen as the effect of such change.

The systematic use of the term industrial revolution was inaugurated in a series of lectures delivered in Oxford by Arnold Toynbee in the early 1880s. He never organized the material of these lectures for publication, but after his death his notes, plus lecture transcripts by some of his students, plus various finished and unfinished essays and occasional writings were collated by W. J. Ashley and Bolton King, under the general supervision of Toynbee's wife, and published as *Lectures on the Industrial Revolution of the Eighteenth Century* (*Popular Addresses, Notes and Other Fragments*) (Toynbee, 1884).

The text is by no means a recognizable economic history of the modern type, and is in fact very wide in scope; this breadth of scope means that it has had multiple legacies. It contains an extended account of the structure of the English economy and English society in 1760 (six chapters), followed by a discussion of the demographic, agrarian and industrial changes of the next eighty years (compressed into one chapter), with one further chapter on the condition and prospects of the working class, and the effects of trades unions and factory legislation. The industrial revolution, at least in Toynbee's initial view, covers a wider range of phenomena than industrialization: it incorporates population growth and other demographic changes; an agrarian revolution comprising the destruction of the common field system, enclosure, and the consolidation of small farms into large; the substitution of the factory system for domestic manufacture; and the expansion of the trade and distribution system. A very substantial portion of the text consists of a discussion of economic theory: there are chapters on mercantilism and commercial policy, on the development of economic theory, on Malthus on diminishing returns and population theory, on Malthus's wage-fund theory, on Ricardian rent and profit theory, on the criticisms of Ricardo by J. S. Mill and Nassau Senior, on the relationship between Classical Political Economy and capitalism, and so on. This way of thinking about coterminous change across multiple social arenas, combined with analysis of intellectual concomitants of change, can be found in major subsequent work, such as Polanyi's *The Great Transformation* (Polanyi, 2001). But the Toynbeean legacy relevant here is his specific concept of industrial revolution.

Toynbee's conceptualisation of the industrial revolution has two elements. On the one hand there is the process of competition that emerged from the social transformations indicated above. The perspective here is that

> The essence of the Industrial Revolution is the substitution of competition for the medieval regulations which had previously controlled production and distribution of wealth. (Toynbee, 1884, p. 64.)

But what joins competition to industrialization is innovation: this connection is registered in the text through the symbolic figures of Adam Smith and James Watt:

> The world was, in fact, on the eve of an industrial revolution; and it is interesting to remember that the two men who did most to bring it about, Adam Smith and James Watt, met in Glasgow, when one was dreaming of the book, and the other of the invention, that were to introduce a new industrial age. (Toynbee, 1884, p.204.)

There are many such passages, in which Adam Smith is seen as having written a programmatic text which Watt makes materially realizable. The view seems to be that however much capitalism resulted from a ramifying process of social change, ultimately it required a specific technological basis. Steam power is in fact causally linked with capitalism: ". . . by the invention of the steam engine Watt *would make possible* the realization of that freedom which Adam Smith looked upon as a dream, a utopia." (Toynbee, 1884, p. 151, our emphasis). But this link also implies a definite line of causation, in which the factory system constituting capitalism is also seen as an effect of technical innovation:

> Passing to manufactures, we find here the all-prominent fact to be the substitution of the factory for the domestic system, the consequences of the mechanical discoveries of the time. (Toynbee, 1884, p.69)

The key industry is cotton. In Toynbee's account "four great inventions" revolutionized cotton production – the spinning jenny, the water-frame, Crompton's mule, and Roberts's automatic spinning mule. But "none of these by themselves would have revolutionized the industry" were it not for James Watt's invention.

The conceptual themes which are established in Toynbee can be found winding their way through almost all of the subsequent major texts of British industrial history. Even in such explicitly technological histories as Landes's magisterial *Unbound Prometheus* (1978) it is possible to find an emphasis on technical change without any developed, systematic theory of the multifarious determinations either of the general impulses to such change, or of specific avenues of technological advance. The failure to treat technical innovation rigorously as an object of explanation opens the way to its treatment as a process sui generis.

At best much of the post-Toynbee literature on the industrial revolution is organized around a systematic explanatory ambiguity which results from the narrative subordination of organizational change – broadly understood – to technique. At worst this tips over, at certain points in the texts, into a more or less straightforward technical determinism. Thus Landes, for example, wrote that, in the cotton sector, "the Industrial Revolution... *required* machines which not only replaced hand labour but *compelled* the concentration of production in factories – in other words machines whose appetite for energy was too large for domestic sources of power and whose mechanical superiority was sufficient to break down the resistance of the older forms of hand production." (Landes, 1978, p.81, our emphases). And Milward and Saul saw various organizational features of economy and enterprise as deriving in a fairly direct way from the requirements of technique: ". . . the joint stock company, the techniques of accountancy and of scientific management were themselves a response to the demands of new technologies." (Milward and Saul, 1979, p.180). The specific propositions of these passages are at least questionable; but that is less important here than the explanatory order which they imply.

A major economic concomitant of technicism is an insistence on capital formation as the primary condition for growth. Although very much a part of modern (especially neoclassical) growth theory, and strongly emphasized by such modern economic theorists of industrialization as Rostow and Lewis, the idea derives its influence from Adam Smith, who proposes it at various places in *The Wealth of Nations*. This is connected to steam by both Toynbee and others; the paradigmatic techniques in which such capital formation is supposed to have been materialized included steam power, a point which was made by the first major historian of steam, John Lord:

> . . . the use of the steam engine (bringing with it the use of true machinery) in any industry meant the presence of much capital in that industry, and the consequence was a large addition to the fixed capital of the country (Lord, 1923, p.184).

Deriving from Toynbee, we thus have a particular conception of industrial transformation with the factory as its site, the steam powered machine as its instrument, and large-scale net investment as its economic basis. This general account has not gone without challenge, however. For a start it runs into serious problems of chronology. Von Tunzelmann himself points out that "if the Industrial Revolution was to be dated from around 1760, as Toynbee believed, then the Watt engine can hardly have triggered off industrialization, since it was not being marketed commercially until the mid-1770s" (von Tunzelmann, 1978, p.3). But even where there is – as in cotton – a clear temporal correlation between expanded output and technical change (e.g. in the period 1760–1800), the causal relations are not at all obvious. On the question of capital formation, there has been a major debate as to whether the British economy did in fact achieve and sustain a rate of capital formation sufficient – at least according to the criteria of Rostow and Lewis – to generate the rates of growth of output, both in the macroeconomy and in specific sectors, which were in fact achieved. A widely accepted conclusion is that British economic growth in the late eighteenth century cannot be accounted for by increased capital formation (Crafts and Harley, 1992). Others have pointed out that the large factory was uncharacteristic in the eighteenth century (Tann, 1970); that the emphasizers of industrialization have seriously neglected agriculture, "the dominant sphere of the economy at this time, and also the most intensively capitalist of any sector" (Tribe, 1978, pp.12–13; Bruland, 2004); that hand techniques persisted in sector after sector until well into the nineteenth century, and that it is therefore "not possible to equate the new mode of production with the factory system." (Samuel, 1977, p. 8). Likewise, it has been argued elsewhere that the factory developed on the basis of hand techniques (Tann, 1970); and that it was the organizational form of the factory which made mechanization possible, not vice versa (Marx, 1976, ch. 15). However in the work of von Tunzelmann, the supposed centrality for early industrialization of the steam engine itself was subjected to decisive challenge.

4. Von Tunzelmann on steam power

Histories of the industrial revolution tend to focus on the (often slow) increases in the rate of growth of total output, and in output per head, which unquestionably occurred (despite serious statistical problems in depicting them) in late eighteenth-century Britain. They tend to ascribe this expansion to the effects of the deployment of new techniques as the primary agent of economic advance, with the strongest version being written around the steam engine:

> If we were to try to single out the crucial inventions which made the industrial revolution possible and ensured a continuous process of industrialization and technical change, and hence sustained economic growth, it seems that the choice would fall on the steam engine on one hand, and on the other Cort's puddling process which made a cheap and acceptable British malleable iron. (Deane, 1965, p.130.)

Von Tunzelmann's work is a quantitative assessment of the validity of such ideas about steam; the aim was "to combine economics, engineering and history to reassess the contribution of the steam engine to British economic growth during the industrial Revolution." Von Tunzelmann is concerned – as we shall describe below – with the differential costs of fulfilment of various technical functions by specific devices; hence, no doubt, his conclusion that "economic theory in isolation may be too abstract a way of interpreting problems of technological change", and his emphasis on engineering relationships.

Two principal techniques are deployed in von Tunzelmann's investigation. The first is taken from the so-called "new economic history" pioneered by R. W. Fogel in his *Railroads and American Economic Growth* (Fogel, 1964); it consists in an assessment of the "social savings" contributed to the economy by steam power. The second technique is a rather more empirical account of the backward and forward linkages of the steam engine in the economy.

5. Social savings

The method pioneered by Fogel is an attempt to isolate the economic impact of any particular innovation; Fogel focused specifically on the US railway system, treating railways as a single major transport innovation.

Fogel states that "I defined the social saving of railroads in any particular year as the difference between the actual cost of shipping goods in that year and the alternative cost of shipping exactly the same bundle of goods between exactly the same points without the railroad" (Fogel, 1979, pp. 2–3). He was insistent that this was a method of analysis of technology impact, and not a historical account in itself:

> ... the social saving is not a description of what actually happened but an answer to a hypothetical problem, a problem similar in nature to those engineers must solve successfully to build bridges or to those manufacturers must confront in choosing between alternative machine designs. This answer rests on a detailed examination of actual economic and technological characteristics of the alternative mode of transportation in historical context. The solution of the problem illuminates actual history not only because it provides a measure of the primary (cost-reducing or resource-saving) effect of railroads in the provision of a specified volume of transportation services, but also because it brings together a great deal of relevant information regarding actual experience and systematically assesses the implications of this information. (Fogel, 1979, pp. 5–6).

The approach is akin to the cost-benefit analysis that might be made by a fully informed rational entrepreneur. Any particular process innovation that enters into production by displacing some prior process, either across sectors of the economy, or by the effective creation of a new sector, diffuses essentially because it cuts total costs of production (whether it diffuses slowly or quickly, via the replacement of worn-out equipment, or by causing functioning plant to be scrapped, will depend on the particular configuration of fixed and variable costs involved). On the basis of the discounted value of the cost reductions the entrepreneur makes a binary decision, to invest or not.

The social savings approach looks at this through a wide lens: with multiple entrepreneurs investing, the sector will see an overall reduction in the capital and labour necessary to produce output. In a full-employment competitive equilibrium these cost reductions can be represented as the difference between the resource costs involved in the old and new modes of fulfilment of some economic function. In turn, such resource-cost differences can be seen as the contribution of the new process to national income. The analysis is carried out via the formation of a counterfactual example: we know what the technical facts were at some point, so let us assume that they were otherwise, and then attempt to quantify the costs of the counterfactual example. The counterfactual is the best available alternative technology. Fogel's counter-example assumed that the American railway network, which many held to be the crucial sector of nineteenth-century American economic growth, was bombed out of existence in 1890; he then calculated the costs of fulfilling the same transport functions through the canal system, animal transport (wagons, stage-coaches etc.), and coast-to-coast shipping around Cape Horn. His conclusion is well-known: the railways contributed less than 5% to U.S. national income in 1890, a striking result which "clashes with the notion that economic growth can be explained by leading sector concepts." (Fogel, 1964, p.236). In one respect this estimate is an upward bound, because Fogel made the assumption that demand for transport was infinitely price inelastic, assuming that there would have been no decline in demand for transport if prices had been higher. But there are further assumptions, that railroad innovation had no effects in term of more effective spatial location of industry, or in terms of induced innovation in other industries, etc. However these issues were addressed by subsequent researchers (see Fogel, 1979 for a discussion). The conclusion is that in a world of technological alternatives single innovations, no matter how dramatic, are unlikely to affect the growth path. This point can also be drawn from one of the few counterfactual approaches to demonstrate large returns: Richard Steckel and William White claim very large returns in a counterfactual-based model of the impact of farm machinery in the USA, but their analysis shows returns not to one heroic innovation, but to a range of innovations working together, over a period consistent with sustained incremental improvements (Steckel and White, 2012).

In his analysis of steam power von Tunzelmann adopted a similar methodology:

> The method adopted is to 'freeze' the traditional technology at its state before the Watt engine took over (i.e. atmospheric engines, water wheels, horse gins, etc.). The object is to obtain the cost structure, so that it will be possible under not too ferocious assumptions to guess what costs would have been in the year 1800, had Watt not gazed at the kettle boiling. That is, the same quantities of metal, wood, fuel, etc., per horsepower are required in counter-factual 1800 as in actual-1769, but priced at 1800 levels. (von Tunzelmann, 1978, p.41.)

This approach is possible because there was no absolute energy blockage to be overcome by the Watt engine during late eighteenth-century economic expansion. The costs of replacing it were not infinite but finite, and calculable. Two cases are worked out: the first examines replacement of the Watt engine alone, the second all types of steam engine. The first case involves the supposition that all Watt engines are replaced by atmospheric steam engines of the Newcomen/Savery types; a difficulty here is that atmospheric engines were not straightforward technical substitutes for the Watt engine because they could not provide the regular "smooth" power required by some textile processes. The costs of the more expensive returning engine technique – in which the atmospheric engine recirculates water to power a water wheel – are therefore calculated. The aggregate fixed and variable savings on the Boulton and Watt engine, and its pirate copies, on plausible patterns of use, are assessed at between £226,000 and £233,000 in 1800. A reasonable estimate of national income in that year is £210 million: thus

> ... the social saving estimated for 1800 is very low even by the normal standards of such reckonings. For Boulton and Watt engines alone (including their pirates) the social savings over atmospheric engines can be put at about 0.11 per cent of national income in 1800. If total real output was then growing at its average rate for the take-off years, the level of national income reached on 1 January 1801 would not have been attained much before 1 February 1801 without James Watt. (von Tunzelmann, 1978, p.286).

A similar, rather more intricate estimate for the replacement of all steam engines by animal and water power places the social savings at approximately 0.2% of 1800 national income:

> If all steam engines, Watt and atmospheric alike, were hypothetically replaced with other means of motive power (a combination of water and wind would be optimal), the setback would have been about two months. These are upward-biased figures. (von Tunzelmann, 1978, p.287).

The other effects investigated in the text are possible backward linkages (into the development of the iron and coal industries) and forward linkages (especially to cotton, via the effects of steam power on the diffusion of automatic machinery in that sector). In opposition to those historians who allege a "mutual sustenance of the steam engine... and the iron industry in the late eighteenth century", it is pointed out that, at the peak of production and sale of Boulton and Watt engines at this period, "their consumption of iron would have amounted to under one-quarter of 1% of annual output" (von Tunzelmann, 1978, p. 286). von Tunzelmann points out that "if all the engines operating in the textile industries had suddenly been swallowed up by the ground in the middle of 1838, and all blast furnace capacity in the country had then been set to work to smelt the iron required to rebuild them, it would have taken under a month to complete the task." (1978, p. 109). Backward linkages to coal were rather more substantial though still arguably very small: possibly as much as 10% of 1800 coal output was consumed in steam engine furnaces, though there are possible upward biases here (1978, see pp. 112–113), and even so "most historians have considered the technical development of coal to have taken place before the Industrial Revolution".

Nor do the forward linkages to cotton look much more impressive: these linkages came relatively late in the development of the cotton sector, "when the cost of supplying power fell and this happened to influence the nature, extent, and mode of employment of machines driven by power" (1978, p. 45), whereas the crucial period of cotton development comes much earlier, in the acceleration of output which occurred between 1770 and 1800. The major technical innovations in cotton, until the development of Richard Roberts's automatic spinning machine in 1825-30, were not developed for steam power: water power long dominated the power-intensive textile processes – "rarely have I unearthed cost reductions from steam-powered inventions in textiles on the scale often intuitively supposed." (1978, p. 294).

The general conclusions reached by von Tunzelmann are not that steam power was of negligible importance for the development of the British economy: rather, "the achievement of steam power in the early nineteenth century was to restrain the kind of pressure on energy costs that would have taken place if resort had had to be made to successively undesirable water sites." (1978, p. 286). But the periodization is important here. Von Tunzelmann shows that steam power did not diffuse on a major scale until the second half of the nineteenth century, when coal prices fell significantly, making steam power a much more viable technological option. But the crucial period of economic growth for the 'first industrial revolution' begins in the second half of the *eighteenth* century, and it is for the economic history of that period, and the early years of the nineteenth century that the prop of steam power has been knocked away.

6. Recent developments in economic history: reassessments and reassertions of the coal-steam nexus

What revisions in the role of steam power in economic history have occurred in the thirty-odd years since von Tunzelmann's book was published? Here we say something of developments in two areas, each subject to strong debate: the continuing literature on steam and the industrial revolution in the UK, and a wider global literature that explores the issue of why the UK in particular and the West in general developed ahead of South Asia and East Asia; in the latter area some have made major claims about coal and steam. Here we are not so much concerned to assess these literatures as to point out the continuing relevance of the themes raised in *Steam Power and British Industrialization*.

Work on the evolution of steam technology and its impacts has continued. Some of this has been essentially focused on mapping the extent of steam power use, essentially confirming von Tunzelmann's estimates (Kanovsky and Robey, 1980). By far the most detailed study of the innovation and diffusion processes of steam has been the work of Alessandro Nuvolari, whose *Making of Steam Power Technology* has shown that steam must be considered as a long-drawn-out process of collective invention, lasting several centuries (Nuvolari, 2004a; see also Nuvolari, 2004b and 2006). Nick Crafts conducted an important growth accounting exercise, seeking to quantify the impact of steam: his conclusions, with a methodology similar to that used for modern assessments of ICT impacts, accorded very closely with von Tunzelmann's: "the results indicate that steam contributed little to growth before 1830 and had its peak impact about a hundred years after Watt's famous invention. Only with the advent of high-pressure steam after 1850 did the technology realize its potential. Compared with ICT, steam's impact on the annual rate of growth was modest" (Crafts, 2004, p. 338).

These perspectives are echoed in the most wide-ranging recent book on the industrial revolution, Mokyr's The Enlightened Economy (Mokyr, 2010). Mokyr's overall assessment of steam is consonant with von Tunzelmann's approach, namely that steam was a radical innovation that took a very long time to have significant economic effects:

> In the popular mind, the Industrial Revolution of the eighteenth century is most widely associated with steam power. This is both correct and misleading. It is correct because the steam engine was one of the most revolutionary inventions ever made by humans, and one that was to have enormous consequences in later years . . . it constituted the first controlled conversion of heat into work and opened up an unprecedented opportunity for harnessing minerals that supplied motive power to production instead of just heat . . . It is important to stress, however, that during the classic years of the Industrial Revolution the immediate impact of steam power on industry and productivity was fairly limited. Much of what steam did before 1830 could have been (and to a large extent was) readily carried out by alternative sources of inanimate power, especially water power. (Mokyr, 2010, pp. 124–125).

Mokyr added: "These statements are only contradictory if we expect technological progress to consist of radical innovations that have a major impact on a wide segment of the economy." (2010, p. 125). These views have been associated with reformulations of the process of technological change during the industrial revolution, broadly speaking stressing either competence development across a very wide range of fields (Meisenzahl and Mokyr, 2011), or the fact that innovation was extremely widely spread across industries and sectors during the first industrial revolution, and cannot be reduced to the macro-inventions of steam and textile technology (for a survey, see Bruland, 2004). These approaches both downgrade the role of steam in early industrial growth, and at the same time offer paths to reconceptualisation of the industrial revolution. They are a legacy of von Tunzelmann's work.

There is however one area of historical research where the "energy crisis" interpretation remains at centre stage. Recent decades have seen the emergence of a substantial literature on global history, focussing on the explanation of major disparities in the levels and growth of incomes and wealth across economic, social and political regions. Such disparities are often sustained for long periods, but are also capable of quite dramatic fluctuations. A

strong theme in this literature has been the rise of the West, and particularly the European breakthrough to sustained productivity growth from the eighteenth century. A major question is whether or not Europe, India, China and Japan (the most studied cases) were in some important ways at similar stages of development until the mid-eighteenth century, leading to the question of why Europe was – on the basis of an underlying similarity – able to initiate innovation-based growth trajectories.

Most of these histories share the view that the sources of modern economic growth do not lie with the industrial revolution, and that although technological events in Britain in the late 18th and early 19th centuries were certainly spectacular, they tell us little about the sources of growth. These sources are seen to lie primarily in social and political changes that ultimately make technology-driven growth possible. Most of these histories focus on institutional changes and related socio-political processes as causal sources of growth. Given the complexity of institutional arrangements this is by no means straightforward: historians such as Robert Brenner, Fernand Braudel, Immanuel Wallerstein, E.L. Jones, Douglass North and David Landes have addressed the links between institutional change and the creation of technological capacity and growth along quite different dimensions. These historians are all in different ways exploring the question of how human society can break from a Malthusian trap, not only in terms of how incentives and opportunities to technological change arise, but also regarding the related issue of how product markets for the outputs of enhanced production can arise. The focus is on the escape from extensive growth, or "Smithian" growth resting on a more graduated division of labour, to intensive growth based on sustained rises in real output per head.

The switch towards institutional explanations of the divergence is a welcome one, but these accounts then need to say something about what institutional change actually did. Here, when the accounts turn to innovation, we frequently find a reassertion of the energy crisis interpretation of industrialization. For example, most of the recent debate among historians has occurred around the work of Kenneth R. Pomeranz's *The Great Divergence: China, Europe and the Making of the Modern World Economy* (Pomeranz, 2000). This widely-discussed work takes the view that prior to the eighteenth century there were no fundamental differences between Europe, Japan and China, with important similarities also vis-a-vis India – this was "a world of surprising resemblances". Pomeranz not only argues for resemblances, but examines pertinent areas of difference between Europe and Asia generally, rejecting many widely-acknowledged differences as being incapable of accounting for the divergence that occurred in the nineteenth century. These differences include an increase in many areas of innovation in the eighteenth century in Europe, improved military technologies, and the growth of luxury markets. Out of this rejection a radical argument emerges, that there were two primary factors that permitted the breakout from Smithian growth. These were the creation of colonies, particularly in North America, as sources of food and raw materials, and the expansion of the supply of coal as a new energy source. Pomeranz rejects Patrick O'Brien's well-known remark that in European industrialization "the periphery was peripheral" and argues that it was crucial both in breaking supply constraints on materials and food, and providing markets for industrial products. On the other hand, Pomeranz really does seem to resuscitate earlier arguments concerning energy constraints in early industrialization, since he also explores the idea of the opportunity-enhancing effects of coal. In Pomeranz it is the growth of the energy opportunities provided by fossil fuels, coal in particular, that shifts the balance. What institutional change does, in the wide sweep of things, is to open up the technological space for steam and coal.

This perspective is argued even more sharply by perhaps the most influential of recent economic histories of British industrialization, namely Robert C. Allen's *British Industrial Revolution in Global Perspective* (Allen, 2009; see also Allen, 2011). Allen's work is by no means a straightforward reassertion of earlier steam-focused accounts of industrialization, mainly because he offers a coherent account of why it is that coal and steam emerged as critical technologies of the industrial revolution. Allen emphasises "the importance of economic incentives as a cause of the industrial revolution" (Allen, 2011, p. 358) with the argument that a combination of high wages and cheap energy made the "breakthrough" technologies of the early 19th century uniquely profitable for British inventors. Echoing but modifying Ashton's remark that steam was the pivot on which industry swung into the modern age, Allen claims that "Britain's unique wage and price structure was the pivot around which the industrial revolution swung" (2011, p. 359):

> The answer to the grand question of how the industrial revolution was related to the early modern economy was this: the commercial and imperial expansion of Britain created a unique structure of wages and prices, and that price structure, in turn, prompted the technological breakthroughs of the eighteenth century by increasing the demand for inventions that substituted capital and energy for labour, and by generating a population that was exceptionally able to respond to those incentives due to its high rates of literacy, numeracy, and craft skills. The spread of scientific culture may have had a reinforcing effect. Some important scientific developments contributed to this advance, but they would not have been acted upon without a demand for the technologies that applied them (Allen, 2011, p. 359)

From one perspective this shares with the work of Pomeranz the perspectives of Arnold Toynbee, in particular a reassertion of the centrality of energy and technique to the industrial revolution.[1] But it is also a theory of induced innovation, with both supply-side and demand-side components. On the supply side there is the claim that both scientific and engineering capabilities had developed to a point that made steam power a feasible project. But it is the demand side that is crucial: British wages rates and coal prices made steam potentially profitable, and elicited search for innovative solutions. So the emphasis is on "the importance of economic incentives as a cause of the industrial revolution" (Allen, 2011, p. 358). The great problem here is that there is no convincing model or data on how a rational innovator might have calculated the costs and benefits of the innovation effort, even though Allen claims that "Watt's career exemplifies the private R&D model of technical change" (Allen, 2009, p. 167). By contrast von Tunzelmann does offer a careful cost-benefit model of the adoption decision, illustrating clearly why the Watt engine diffused rather slowly until the price of coal fell in the 1860s (85 years after the main Watt patent). The real issue here is not so much that Allen offers a neo-classical account of incentives to innovate, but rather that he fails to take on board the idea that the industrial revolution might involve multiple technological advances over a long time period, and thus need a much wider analytical framework.

As opposed to these views, within this "global perspective" literature there are contributions that specifically recognize the implications of von Tunzelmann's work: the recent wide-ranging study of global divergence by Prasannan Parthasarathi, *Why Europe*

[1] There is an almost direct echo of Toynbee in Allen's remark that "The famous inventions – the spinning jenny, the steam engine, coke smelting, and so forth – deserve their renown, for they mark the start of a process that has carried the west, at least, to the mass prosperity of the twenty-first century". (Allen, 2011, p. 357). It could be argued that Allen's incentive-based approach is compatible with multiple lines of technological advance; the real problem is the issue of uncertainty, which affects all innovations and clouds the forms of calculation that he emphasizes.

Grew Rich and Asia Did Not, is a particularly interesting example (Parthasarathi, 2011). Parthasarathi's work not only reviews von Tunzelmann's social savings approach and his study of the use of steam in the textiles sector, but also points to Raphael Samuel's work on hand technologies accompanied by pervasive organizational change as a more appropriate approach to understanding early industrial growth (Parthasarathi, 2011, pp. 154–157). However even here there is something of a hesitation, because in his discussion of 18th century growth in England he later points to a "new energy complex" of which "the steam engine and the use of coal in manufacturing were the two key elements", despite the fact that he also recognizes that the predominant use of coal throughout early industrialization was for domestic heating (Parthasarathi, p. 161).

7. The continuing relevance of von Tunzelmann's work

In our view von Tunzelmann's conclusions definitively break the nexus between steam, industrialization and capitalist development which, established by Toynbee, had sustained so much of British economic historiography. His work in assessing the scope and size of the impact of steam power on the British economy extends, it should be emphasized, beyond the period and apart from the theoretical theme which we have stressed here. We have chosen to accentuate what we see as its implications for the historiography of the so-called first industrial revolution. We ought to note that von Tunzelmann's approach is completely consistent with results in a wide range of studies in innovation economics concluding that major technological breakthroughs often require very long periods of post-innovation improvement before they can have significant economic impacts. Nathan Rosenberg pointed this out (incidentally in the context of the Watt steam engine) some time ago:

> . . . even if we date the steam engine from Watt's accomplishments of the 1760s and 1770s, it still took a full century of improvement and design change before this new power source surpassed water power in manufacturing and displaced the sail on ocean going vessels. The essential point to be grasped here is that inventive activity is best described as a gradual process of accretion, a cumulation of events where, in general, continuities are much more important than discontinuities. Even where it is possible to identify major inventions which seem to represent entirely new concepts and therefore genuine discontinuities, there are usually pervasive technological as well as economic forces at work which tend to slow down and to flatten out the impact of such inventions in terms of their contributions to raising resource productivity. (Rosenberg, 1976, p. 192)

What are the implications of such ideas for a more nuanced account of British industrialization? Any displacement of the energy-crisis interpretation and the critical technologies approach might involve two separate lines. The first requires a greater priority to the complex of non-technical elements of the capitalist economy – such as managerial practices – in the analysis of growth and structural transformation. It is a sad index of the dominance of technicism that what remains the best study of the construction and effects of managerial systems in industrialization, Pollard's *Genesis of Modern Management* (1965), concluded that "among the many competing explanations there can surely nowhere be a managerial theory of industrial revolutions" (1965, p. 271). Hartwell long ago pointed out that this conclusion contradicts not only modern economic ideas about growth, but also Pollard's own detailed results. (1971, p. 300). Samuel showed rather convincingly, in possibly the most extensive set of case studies ever assembled in this area, that intensified work organization as a result of new managerial control was central to early "industrial" growth. The second line of approach involves a reassessment of the causal determinants of technological change, its sectoral spread, and its directions. It should not be paradoxical for us to assert that technological change is of great and sometimes unique importance in economic growth, for the technological determinism of the critical technologies approach conceals the true determinants of such change as much as it conceals structural and organizational change. The weakness of the critical technologies approach does not stem from the fact that it emphasizes the importance of innovation, but from the place which it assigns to innovation in the order of explanation. Changing the energy constraints and the energy balance were central to long run economic growth (as Wrigley, 2010 emphasises), but the technologies that enabled this were not causes but effects of a society engaged in innovation.

More generally, we need to recognize the extent to which the critical technologies account of early industrialization links to much wider issues related to the idealisation of early inventors, and the place of invention and technology in cultural and political conflicts that are far from resolved. Christine MacLeod, in *Heroes of Invention*, points to Watt not simply as a key figure in technological history, but as someone whose legacy was quite specifically constructed after his death in order to buttress liberal and commercial interests:

> James Watt was posthumously fashioned into the standard-bearer of the rising industrial classes. He personified their claim that it was not military prowess that made Great Britain great, but the ingenuity and enterprise of its 'industrious' citizens: the country's strength and global influence rested on the prosperity generated by manufacturing and trade . . . (MacLeod, 2007, p. 1, see also pp. 91–124).

In his early work Nick von Tunzelmann initiated a fundamental breakthrough in our understanding of the origins, paths and effects of industrialization. This breakthrough has been followed through, on a number of dimensions, by historians of technology and economic historians. Both von Tunzelmann's work and more recent work on innovation in the industrial revolution have wide implications for how we view the dynamics of the industrial world economy. The main point of this work is that steam was not the driving causal factor that has been found in so much economic history. Rather it is one technology among many, and was itself driven by complex social, institutional and political shifts, and by a long accretion of knowledge. Despite the recent reassertion of the critical technology interpretation of industrialization, in the work of Pomeranz, Allen and others, the deeper implications of von Tunzelmann's path-breaking work are continuing to inspire scholars, and continuing to be incorporated into the economic history of industrialization and industrial dynamics.

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